

Electron as Spatiotemporal Complexity due to Self-Organized Criticality

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Abstract

The electron, which has been pictured as an elementary particle ever since J.J. Thomson's e/m -measurement in 1897, and the relativistic motion of which is described by the Dirac equation, is discussed in the light of the recent progress made in Science of Complex Systems. Theoretical arguments and experimental evidences are presented which show that such an electron exhibits characteristic properties of spatiotemporal complexities due to Self-Organized Criticality (SOC). This implies in particular that, conceptually and logically, it is neither possible nor meaningful to identify such an object with an ordinary particle, which by definition is something that has a fixed mass (size), a fixed lifetime, and a fixed structure.

The electron has been pictured as a particle, and as one of the elementary building blocks of nature, ever since J.J. Thomson published the result of his e/m -measurement in 1897¹. The Dirac equation²⁻⁴, originally designed as an one-particle equation, which describes the relativistic motion of such an electron (e) in the framework of Quantum Theory, is undoubtedly one of the greatest achievements in physics — although the original goal failed. This is because, it is Dirac's equation which predicted the existence of positron and thus led to the discovery of one of the general fundamental symmetries (the charge-conjugation symmetry) in nature^{3,4}; and because, it is also this equation which describes in general the relativistic motion of all the known (electrically charged) spin-1/2 objects, in particular, that of the heavier leptons (μ , τ), as well as that of the quarks (u , d , s , etc) which are

the constituents of hadronic matter^{5,6}. The purpose of this letter is to point out that the above-mentioned electron exhibits characteristic properties of spatiotemporal complexities due to self-organized criticality (SOC)⁷⁻¹⁰. Hence, among other things, it is neither possible nor meaningful to identify such an object with an ordinary particle which, by definition, should have a fixed size (mass), a fixed lifetime, and a fixed structure. The theoretical arguments and experimental evidences which lead to this conclusion can be summarized as follows: Two of the fundamental symmetries in nature, namely the invariance under charge conjugation transformation and that under (Abelian) local gauge transformation, which is also known as the gauge principle⁶, dictate the following: The validity of Dirac's equation for the spin-1/2 charged fermions e, μ, \dots, s, c , etc. implies not only the existence of the corresponding antifermions $\bar{e}, \bar{\mu}, \dots, \bar{s}, \bar{c}$, etc., but also that the pairs made out of the above-mentioned fermions and antifermions interact with the electromagnetic field in one and the same manner. This means in particular that, electromagnetic interaction can produce transitory virtual pairs $e^+ - e^-, \mu^+ - \mu^-, \dots, s - \bar{s}, c - \bar{c}$, etc. in the same "vacuum". Taken together with the fact that all Dirac fermion fields fluctuate^{2-4,11,5,6}, the picture we obtain for "the electron", by examining it in a spatial region within its Compton wavelength, is the following: It is always closely associated with — in fact inseparable from — "the vacuum" which consists of an indefinite number of all kinds of transitory virtual fermion-antifermion pairs ($e^+ - e^-, \mu^+ - \mu^-, \dots, s - \bar{s}, c - \bar{c}$, etc. with various indefinite lifetimes) where the total number, as well as the relative abundance, of such pairs are in general different in different regions of space-time. In other words, "the electron" has to be considered as an open dynamical complex system of an indefinite number of degrees of freedom. Precisely speaking, "the electron" is a typical spatiotemporal complexity due to SOC⁷⁻¹⁰. The proposed picture, in which "the fluctuating vacuum polarization" deduced from Dirac's equation^{2-4,11,5,6} is viewed as an integral part of nature, can be readily tested by comparing it with the available electron-positron collision data¹²⁻¹⁴. The results of such tests strongly support the picture.

It has been pointed out some time ago by Bak, Tang and Wiesenfeld^{7,8} that striking

simple regularities exist in many seemingly disparated open dynamical complex systems far from equilibrium. Based on the fact that the same regularities appear in many seemingly not comparable systems in the macroscopic world — from the formation of the landscape to the process of evolution to the action of nervous systems to the behaviour of the economy — it is natural to ask^{9,10} whether such regularities are so general and so universal that they are true also in the microscopic world. The questions we discuss in this paper are the following. Down to what level can we find such open dynamical complex systems? What is an “electron”, the motion of which is described by the Dirac equation? Can such an “electron” indeed be viewed in the way we usually do in the conventional picture (see below for more details), namely as an ordinary particle which should and can have a fixed mass, a fixed lifetime, and a fixed (in particular point-like) structure?

We recall that the picture of “the electron” (it will hereafter be referred to as “the conventional picture”) in the renormalized Quantum Electrodynamics (QED) which is based on the validity of Dirac equation for “the electron” and the validity of Maxwell equations for the electromagnetic field) can be described as follows^{5,6}: Similar to the corresponding picture in Classical Electrodynamics, “the electron” is, also in this case, a stable particle, because no “excited electron” and no “electron-decay” has been observed experimentally. Its mass (m_e) and its charge (e) have fixed values; and these values can be, and have been, determined (by measuring e/m_e and m_e/m_H where m_H is the mass for the hydrogen atom, or by measuring “the elementary charge” a la Millikan) by performing experiments at low velocities, which means that they are measured at spatial distances large compared to the electron Compton wavelength $1/m_e$. But, “the electron” which is loosely called “a point charge in vacuum” must, on the other hand, be envisaged as being surrounded by an induced charge distribution that steems from transient $e^+ - e^-$ pairs produced by the electromagnetic field of “this point charge”. Precisely speaking, according to perturbative QED calculations, distribution of the induced charges extends out to distances of order $1/m_e$, and is a small and diffuse effect except at distances vastly shorter than those currently attainable by experiment. Note that this conclusion is reached under the assumption that the Fourier transform of a static

charge distribution (known as its “electromagnetic form factor”) can be used to describe the electromagnetic structure of a spatially extended object, not only in the non-relativistic limit of slowly moving particles, but also in describing those in relativistic scattering processes. In fact, “the size” of the charged lepton (e, μ, τ) has been determined by examining the deviations of their electromagnetic form factors from unity (by definition “structureless”) in high-energy collision processes such as $e^+ + e^- \rightarrow \mu^+ + \mu^-$, $e^+ + e^- \rightarrow e^+ + e^-$. These, as well as other related facts show that, when we use the conventional picture for “the electron”, it is of considerable importance to keep the following in mind: The claim that the leptons are point-like *stems from theory*. The observation of an object’s structure *involves not only a probe, but also a detailed knowledge of that probe’s interaction with the object*. In the conventional picture, the probe is electromagnetic field, and the probe’s interaction with the object is described by QED and other related theories/models in particular the above-mentioned assumption about electromagnetic form factors. Here, it is of particular importance to recall that, due to electromagnetic interaction, charges radiate, and such radiation also interacts with the emitting charges. By taking these effects into account, perturbative QED calculations yield a diverging expression for “the self-energy” which contributes to the physical mass, and a diverging expression for “the induced charge” due to “vacuum polarization”. Finite results are obtained by performing the renormalization procedure in the following way: “Renormalized quantities”, “the renormalized mass” and “the renormalized charge” (also known as “the dressed charge”), are introduced into QED. They are defined as the differences between the above-mentioned diverging expressions and the quantities which originally appear in the Dirac equation for “the electron” in electromagnetic field. The original mass and charge are called “the bare mass” and “the bare charge” respectively, and both of them are assumed to be infinite. The “renormalized quantities” are finite; their values are obtained by identifying them with the corresponding measured quantities in low-velocity experiments where the measurements are made at distances larger than the electron Compton wavelength $1/m_e$. This means, not only “the point-like structure”, but also “the mass”, “the charge”, and “the lifetime” of “the electron” in the conventional

picture are *theoretical inputs* which are *additional rules* set up in a self-consistent way to avoid the infinities originate from “the fluctuating sea of negative-energy electrons” in the Dirac theory.

In short, the conventional picture for “the electron” in the framework of QED is obtained through a straightforward modification: The concepts and methods which have been used to describe a charged particle in classical physics (mechanics and electrodynamics) are replaced by the corresponding ones in quantum physics (quantum mechanics and quantum field theory). But, such a modification leads to *conceptual*, *logical*, as well as *computational* difficulties, and almost all of these difficulties are intimately related to the properties of the Dirac equation. The *computational* difficulties have been circumvented by introducing “the renormalized mass”, “renormalized charge” etc. for “the electron”. While good agreement between the measured results and the above-mentioned theoretical inputs has been achieved, *the difficulties* caused by the fluctuations of “the negative-energy electrons” in the Dirac theory *have not been removed*.

The importance of the above-mentioned *conceptual* and *logical* difficulties in the Dirac theory *cannot* be exaggerated. Due to the fact that QED is based on Dirac’s equation on the one hand, and the fact that “the electron” *is assumed* to be a structureless point-like particle is in sharp contrast to the nature and the spirit of the Dirac equation on the other hand, it is not difficult to understand why many concerned physicists *cannot* accept the idea that the present form of QED (and/or that of the Electroweak Theory) should already be *the final version* of a quantum theory for the relativistic motion of an electron in electromagnetic field. In this connection, it is perhaps of some interest to recall what Dirac wrote — as the last sentence — in his book published in 1958⁴: “The difficulties, being of a profound character, can be removed only by some drastic change in the foundations of the theory, probably a change as drastic as the passage from Bohr’s orbit theory to the present quantum mechanics.”

Due to the tremendous success — mainly caused by the existence of “negative energy solutions” — the Dirac equation *has not been* and *should not be* abandoned, although it

is known almost immediately after its discovery^{2-4,11,5,6}, that it *cannot* be an one-particle equation. But in QED, “the electron” is by definition a particle with a fixed mass and a fixed structure, the motion of which is described by Dirac’s equation. Hence, as a first step towards a possible removal of the conceptual and logical difficulties, where a “drastic change” cannot be avoided, it is perhaps of some interest to find out the following: Are there *compelling reasons* which *force* us to accept the theoretical input, that “the electron” *should* be viewed as an ordinary particle with a fixed mass, a fixed lifetime, and a fixed structure? If not, why can we not abandon the additional theoretical inputs, and accept the logical consequences of the Dirac theory and those of the gauge principle? To be more precise, why can we not accept that the virtual fermion-antifermion pairs in “the vacuum” indeed play a significant role — especially when “the electron” is localized within its Compton wavelength? Why can we not simply accept that “the electron” is inseparable from an indefinite number of fermion-antifermion pairs which are fluctuating all the time and everywhere? In other words, why do we not simply accept that “the electron” should be considered as an open dynamical complex system?

Once we agree to accept this, the next question we have to face is to find out whether it is possible to probe such open dynamical complex systems experimentally — especially to probe “the interior” of such a system within the electron Compton wave length. Besides the well-known fact⁶ that the effects of “negative energy solutions” of the Dirac equation are particularly significant in this region, there are also other reasons why this region is of particular interest: (I) The validity of the uncertainty principle and the special relativity theory dictates that the distance between the members of a virtual pair due to vacuum polarization cannot exceed the corresponding Compton wavelength. This implies in particular that the distances between the members of a $s - \bar{s}$ or a $c - \bar{c}$ pair are much shorter than that between the members of an $e^+ - e^-$ pair, and thus it is expected that the effects on charge distribution caused by the former can be detected only when the distance between the probe and the object under investigation is much smaller than the electron Compton wavelength. (II) It is within this region, where the theoretical inputs in the conventional picture have

been used to circumvent the diverging results obtained by performing perturbative QED calculations.

Can we find *experimental* means to probe “the *interior*” of “the electron” —without making use of the above-mentioned theoretical inputs? To be more precise, can we answer the following questions? (A) Are there experiments in which we can see that, not only virtual $e^+ - e^-$ pairs, but also *virtual pairs of heavy objects* (e.g. $s - \bar{s}$ and $c - \bar{c}$) *exist* in “the vacuum” which is intimately associated with, in fact inseparable from, “the electron”? (B) Are there experiments in which we can see that such created virtual $s - \bar{s}$ and $c - \bar{c}$ pairs of “the electron” can “disappear” in the sense that such heavy pairs turn into radiations and thus “return to the vacuum”? In other words, are there experimental evidences that such heavy quark-antiquark pairs can turn into something which behave very much the same as electromagnetic radiation? (C) Are there experiments which show how the emergence and the extinction of such virtual fermion-antifermion pairs take place? Is it possible to extract information about the emergence-extinction processes from the existing experimental data?

As can be seen in more detail below, a simple and convenient way to examine “the interior” of “the electron” and/or that of “the positron” is to let these two objects get as close as possible to each other in space-time such that we can also examine the various effects caused by energetic quark-antiquark pairs. Here, we make use of the following (empirical, actually rather trivial) fact. The resulting system formed by two open dynamical complex systems with the same kind of ingredients is again an open, dynamical, and complex one. Under normal conditions (e.g. not at certain “resonance energies” where certain special reactions may take place), it is expected that their characteristic properties also remain unchanged. For example, the resultant system formed by two systems far from equilibrium remains to be far from equilibrium. Having this in mind, we now look at the available data^{6,12–14} obtained from high-energy electron-positron collision experiments. To be more specific:

(A) We examine the characteristic features of the well-known^{6,12} ratio $R(w) = \sigma_T(e^+ + e^- \rightarrow \text{hadrons}; w) / \sigma_{\mu\mu}(e^+ + e^- \rightarrow \mu^+ + \mu^-; w)$, where σ_T , $\sigma_{\mu\mu}$, and w stand for the to-

tal cross-section, the integrated cross-section for $e^+ + e^- \rightarrow \mu^+ + \mu^-$, and the total c. m. s. energy of the $e^+ + e^-$ system respectively; and we examine in those two kinds of reactions the characteristic features of the angular distributions of the produced hadrons. The observation^{6,12,13} that $R(w)$ appears approximately as ascending steps for increasing w , where every jump corresponds to a threshold at which the creation of a quark-antiquark pair of a given flavour becomes possible; as well as the observation¹³ that the produced hadrons appear mainly in two jets where the forward- and the backward-directions are preferred, show that the question raised in (A) should be answered in the affirmative. In other words, these experimental facts show that there are not only virtual $e^+ + e^-$ pairs but also virtual heavy objects such as quark-antiquark pairs, distributed in the region within the electron Compton wavelength of the colliding electron/positron. The reasons which lead us to this conclusion are the following: Hadrons are colour-singlets, and the overwhelming majority of the produced hadrons are flavour-neutral which can be formed only when suitable energetic quarks and antiquarks associated with the colliding electron/positron can meet and interact with each other. At sufficiently high incident energies, the members of such fermion-antifermion (i.e. either lepton-antilepton or quark-antiquark) pairs are in general energetic, and their momenta are mainly in the direction of the colliding electron/positron. Every quark (or antiquark) has the chance to meet another suitable partner to become a hadron. Virtual quark-antiquark pairs such as $s - \bar{s}$ and $c - \bar{c}$ may also become physical (real) by acquiring energy from other virtualpairs (of any flavour). Forward- and backward-directions are preferred, because of momentum conservation. As w increases, more and more varieties of heavier quarks/antiquarks can be created, and thus the chance for the production of energetic and physical heavy quark-antiquark pairs becomes larger. We note that pairs of heavy quark-antiquark may also appear as meson-resonances with various quantum numbers at resonance-energies.

(B) We examine the yield of $\mu^+ - \mu^-$ pairs in the final state of the reaction $e^+ + e^- \rightarrow \mu^+ + \mu^-$, and look for interference effects in the neighbourhood of the above-mentioned thresholds. The fact that spectacular interference effects have been observed¹² in the neighbourhood of

the f - and in that of the J/ψ -resonances show that the questions raised in (B) should be answered in the affirmative. This is because, as mentioned in (A), the existence of virtual quark-antiquark pairs in “the electron” and “the positron” implies, that at sufficiently high incident energies, virtual as well as real quark-antiquark pairs — including meson-resonances — can be formed, and some of them (any sort of them, in particular the resonances) may have the same quantum numbers as those of the photon. In terms of the usual quantum mechanical description, the amplitude of a resonance is complex — in contrast to that of a photon which is real. Hence, measurable interference effects are expected when the above-mentioned process takes place near the resonance-energies. We note that the reason for examining such effects in the $e^+ + e^- \rightarrow \mu^+ + \mu^-$ rather than in the $e^+ + e^- \rightarrow e^+ + e^-$ channel is that although in both cases, the intermediate state can have quantum numbers same as the photon, but only in the former case, no identical particle and/or “cross-channel contribution” effects need to be taken into account. We also note, the observation¹² of such interference effects explicitly shows that not only lepton-antilepton pairs but also quark-antiquark pairs disappear in the same way as they emerge in “the vacuum” which is an integral part of “the electron” and/or “the positron” described by the Dirac equation(s)!

(C) We examine the energy (w)-dependence of the integrated cross-section ($\sigma_{\mu\mu}$) for the reaction $e^+ + e^- \rightarrow \mu^+ + \mu^-$ at sufficiently high total c. m. s. energies (w 's). The fact that almost all (as expected, the only exceptions being those in the vicinity of the weak gauge boson Z .) the available data points¹⁴ lie on one straight line with a slope -2 in the $\log \sigma_{\mu\mu}$ vs. $\log w$ plot (cf. Figure 1) show that also the questions in (C) should be answered in the affirmative. It is because this plot shows how the lifetimes of such virtual pairs are distributed. Note in particular that, in general, such virtual pairs are already present either as “part of the electron” or “part of the positron” before the two open dynamical complex systems come close (of the order of electron Compton wavelength, say) to each other, and we examine those extinction processes which take place in the resultant open system, when members of high-energy virtual pairs find their suitable high-energy suitable partners and thus “return to the vacuum”. To be more specific, the plot clearly shows the following: First,

there are strong experimental indications that the ingredients of “the electron” are changing all the time and thus it is neither meaningful nor possible to say that “the electron” is a particle with a fixed mass, a fixed lifetime, and a fixed structure. Second, the evolution of the various virtual pairs in “the electron” obeys the same law as the kill-curve discovered by Raup^{15,8} for biological evolution — a particularly striking fingerprint of self-organized criticality SOC^{7–10}.

In order to see explicitly how the above-mentioned conclusions have been reached, it is useful to keep the following in mind.

(I). Fermions and antifermions can in general recombine. Although the detailed interactions between fermions and antifermions as well as those between the pairs are in general different, such details do not play a significant role as far as the lifetime distribution is concerned, provided that they are constituents of an open dynamical complex system due to SOC^{7–10}. (II). The lifetime (τ) of virtual constituents of a system — such as “the electron” or the resultant system — can be estimated by making use of the uncertainty principle and the basic ideas of Feynman’s parton model¹³. The result, which is now well-known¹³, is that, in the c. m. s. frame of “the electron” and “the positron”, the lifetime of a virtual object in either of them is directly proportional to the magnitude of the total longitudinal momentum of either one of the colliding objects, and thus it is directly proportional to w , the total c. m. s energy of the above-mentioned colliding system. Hence, the τ -dependence of the probability for a virtual pair of fermion-antifermion to disappear, that is “back to vacuum”, by turning into a $\mu^+ - \mu^-$ (either through recombination or through acquiring energy from other pairs) is directly proportional to the w -dependence of this probability. We note that the latter is nothing else but the integrated cross-section (w) for $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

In conclusion, not only theoretical arguments, but also the existing high-energy electron-positron collision data^{12–14}, strongly suggest that “the electron” described by the Dirac equation^{2–4} is a spatiotemporal complexity due to self-organized complexity^{7–10}. It is indeed a remarkable fact that the emergence and extinction of various types of virtual fermion-antifermion pairs in “the electron” and the emergence and extinction of various

genera on earth obey one and the same law^{15,8!}

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FIGURES

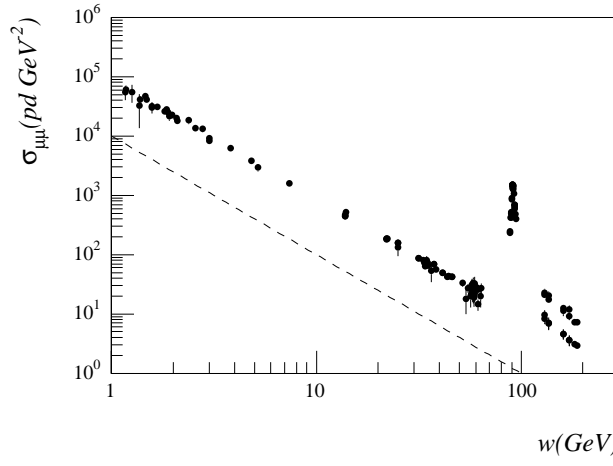


Fig. 1. The integrated cross-section $\sigma_{\mu\mu}$ for the reaction $e^+ + e^- \rightarrow \mu^+ + \mu^-$ is plotted as function of the total c.m.s energy w of the $e^+ - e^-$ system. The existing data, taken from Refs.[12-13], lie approximately on one straight line in this log-log plot. The dashed line is drawn to show that the slope of the is line is -2, and thus it is exactly the same as Raup's "kill-curve" for biological evolution [15,8].